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FUSION ENERGY DEVELOPMENT

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NUCLEAR DATA
SUBJECT TO RECALL
IN TWO WEEKS

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ABSTRACT

Under the auspices of the Office of Basic Energy Sciences of the Department of Energy, a program has been under way for the past seven years to meet the high-priority nuclear data needs of the Office of Fusion Energy. Ten laboratories now participate in this program and provide experimental data on low energy charged-particle reaction cross sections including the basic fusion reactions, neutron scattering and emission data, cross sections for charged-particle emission and helium production, and standards data. This measurement program also emphasizes the development of new tools to meet future needs for data measurements and for more reliable calculations of the required nuclear data.

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INTRODUCTION

To focus nuclear data measurement activities on the needs for fusion development, a program to meet the high-priority nuclear data needs of the Office of Fusion Energy (OFE) of the US Department of Energy (DOE) has been under way for the past seven years. This program, under the auspices of the Office of Basic Energy Sciences (BES) office of the DOE, now includes work at 10 institutions to satisfy the broad spectrum of needs for nuclear data measurements.

The development of nuclear fusion energy depends to a great extent on the underlying technologies, and in particular on the nuclear data base. We must know for example the rate of the fusion reactions themselves, nuclear interactions useful for indicating the state of the plasma, reactions of neutrons in the blanket, heat-producing nuclear reactions, activation of materials and the possibility of burnup of those radioactive species, and a wide variety of nuclear interactions that lead to radiation damage of materials. The nuclear data needs for fusion energy development were surveyed recently.¹ Although the data base that the fusion community uses directly is often an evaluated data library, the reliability of these data and the techniques used to obtain them depend ultimately on direct experimental measurements, which is the focus of this BES program.

The BES program includes measurements of fusion reaction cross sections at low energies; elastic and inelastic neutron scattering; neutron, charged-particle, and gamma-ray emission cross sections, spectra, and angular distributions; cross sections for $(n, {}^4\text{He})$ reactions; and measurements of standard cross sections at the fusion neutron energy of 14 MeV (see Table I). This program has been very successful in providing measurements of nuclear

data requested by the Office of Fusion Energy. The accomplishments and activities of the program in light of the current request list were reviewed recently.²

In this paper we summarize the scope of the program and give examples of the data obtained. Because of the many contributions by the participating laboratories, not all of the work can be covered and the reader is referred to reference 2 for a more detailed presentation. We also will emphasize several of the new techniques developed to meet the present and future nuclear data needs for fusion energy development.

LOW ENERGY CHARGED-PARTICLE REACTIONS INCLUDING THE BASIC FUSION REACTIONS

The possibility of fusion energy rests fundamentally on fusion reactions, which for the early generation reactors will be the $T(d,n)^4\text{He}$ and $D(d,n)^3\text{He}$ reactions. In addition, other reactions, perhaps using deliberately injected impurities, are proposed to determine the properties of the plasma. Two approaches are being taken to address the cross sections for these reactions.

The accuracy of the cross section data for the D-T, D-D and T-T fusion reactions was brought into question several times in the past decade (see for example Ref. 3). The measurements required were for very low charged-particle energies (down to 10 keV or so) and therefore extremely thin targets and well-known beam energies were essential. To attack this problem a facility for Low Energy Fusion Cross Section measurements (LEFCS) was constructed at the Los Alamos National Laboratory (Fig. 1). This facility utilizes the existing tandem van de Graaff accelerator for probing the target which is a windowless gas cell of deuterium or tritium gas. A low energy accelerator accelerates a deuteron or triton beam to the gas cell. The results from this

investigation so far have pinned down the D-T cross sections to an equivalent incident deuteron beam energy of 8 keV (see Fig. 2) and the D-D cross section to 20 keV with uncertainties of a few percent, certainly sufficient for use in the foreseeable future. The measurement of the T-T cross section is planned for the next year. Dr. G. M. Hale will have more to say about the D-D and D-T cross sections in this session.

Nuclear data for characterizing the plasma are underway both at Los Alamos and at the Colorado School of Mines (CSM). At both institutions the $T(d,\gamma)^5\text{He}$ cross section is being investigated since this reaction could be a useful indicator of the spatial distribution of fusion reactions in the plasma. (The product gamma rays might be detected more cleanly than the neutrons from the other branch, $T(d,n)^4\text{He}$). Preliminary data have been obtained at different incident energies at these laboratories. In addition at CSM other reactions that might be used to infer plasma properties have been investigated such as (d,n) reactions on ^6Li , ^9Be , and ^{10}B , (d,p) reactions on ^6Li , ^9Be , and ^{10}B , and the $^7\text{Li}(t,\alpha)^6\text{He}$ reaction. The use of these reactions would require injection of the appropriate impurity into the plasma. One interesting aspect to this later research project is that the detector used for gamma ray detection (a large sodium iodide detector with a split NaI annulus) is earmarked for future use in characterizing plasmas at major fusion experimental facilities.

NEUTRON SCATTERING AND NEUTRON EMISSION MEASUREMENTS

Neutron scattering measurements, including inelastic scattering and some neutron emission, are being investigated at Triangle Universities Nuclear Laboratory (TUNL) and at Ohio University with monoenergetic neutron sources. Much work has been devoted to the light nuclei, that is oxygen and lighter, because of the difficulty of calculating these cross sections reliably from

any a priori nuclear model. The data situation for these needed cross sections has been improved markedly as a result of the BES program at these two laboratories (see Fig. 3).

The scattering of neutrons from heavier nuclei has been investigated at TUNL and has been extended to the scattering of polarized neutrons (Fig. 4). Although the latter data have not been requested for fusion neutronics, the measurements are valuable in determining parameters of the optical model which is used generally to calculate the elastic scattering of neutrons. The refining of the optical model gives the nuclear data evaluators an improved tool for providing data for fusion applications.

At the Oak Ridge National Laboratory a different approach has been taken toward the study of neutron scattering and emission, that is the use of a white neutron source from the Oak Ridge Electron Linear Accelerator (ORELA). These measurements complement those with monoenergetic sources in that they span easily a wide range of incident neutron energies and that neutron emission can be measured in ranges that are difficult with monoenergetic sources such as the 8 to 13 MeV range. The tradeoffs are that measurements with good angular resolution, particularly for elastic scattering, are not yet possible and that the precision of the data, where the monoenergetic source results can be compared, is generally somewhat worse. Figure 5 gives an example of results from the ORNL work.

NEUTRON-INDUCED GAMMA-RAY EMISSION

The production of gamma rays from neutron interactions is a major part of the ORNL activity in the BES program. These measurements, made with the white neutron source at the ORELA, are important for calculations of energy transport in reactor designs and for studies of transmutation cross sections. The former application is obvious from fission reactor experience. The latter

transcends much of the fission reactor examples since many new reaction channels are open at the higher neutron energies in fusion reactors. For example, gamma rays in the residual nucleus can indicate the individual cross sections for (n,n') , $(n,2n)$, (n,p) , and (n,α) reactions, all of which might be possible at these higher energies (up to 14 or 15 MeV) (see Fig. 6). For application to fusion materials testing accelerators, which could produce neutrons up to 40 or 50 MeV, the separation of these and additional reaction channels could be even more important. The ORNL approach also is appropriate for these higher energies (Fig. 7). These new channels can have effects in radiation damage or as diagnostic reactions to indicate the spectral distribution of neutrons at the position of dosimetry foils.

NEUTRON-INDUCED CHARGED-PARTICLE EMISSION

Reactions of neutrons that result in charged particles are basic transmutation reactions that can have important effects in radiation damage of materials, in activation, and in the calculation of energy deposition. Radiation damage can result from the buildup of hydrogen and helium in materials when the light charged-particle reaction products (protons, deuterons, tritons, and alpha particles) stop in the material, capture atomic electrons and become hydrogen or helium implanted in the material lattice. The effects of these gases are being investigated and their importance on potential materials will depend on the production cross sections for the charged particles.

These reactions often yield radioactive products which can affect the operation, maintenance, and ultimate decommissioning of a fusion reactor. The study of the $(n, \text{charged particle})$ reactions is complementary to the direct study of the radioactive product nuclei. Because of the greater physics information in the charged particle emission spectra and angular

distributions, more stringent tests of the nuclear reaction model calculations are provided by the (n,charged particle) data than by activation measurements.

The calculation of the energy deposited by charged particles depends directly on (n, charged particle) reaction data. The kerma factor (for kinetic energy released in materials) is a quantity commonly used in microscopic calculations of dosimetry.

Two laboratories in the BES program are investigating the (n,charged particle) reactions. At Ohio University and at Lawrence Livermore National Laboratory quadrupole spectrometers serve to transport the charged particles from the nuclear reactions to detectors that are in a low background environment several meters from the target foil and the neutron source (see Fig. 8). Other transport systems are also being investigated at these institutions including electrostatic guiding fields and simple evacuated time-of-flight tubes (Fig. 9). Reactions with neutron energies near 14 MeV, where the neutron source strength is high, have been investigated in detail for many materials. More recently other neutron source energies are being used. Some typical data are compared with nuclear reaction model calculations in Fig. 10.

HELIUM ACCUMULATION MEASUREMENTS

Complementary to the (n, charged particle) measurements is the direct detection of helium isotopes following bombardment of samples by neutrons. At Rockwell International, especially sensitive mass spectrometric techniques have been developed to determine low levels of helium in materials (see Fig. 11). The results of these studies are in agreement with data integrated from the (n, charged particle) measurements and have smaller quoted error bars (Table II).

STANDARDS MEASUREMENTS

Recently investigations to supply standards data have been added to the BES program. These studies, at the Universities of Michigan and New Mexico, concentrate on the measurement of cross sections that have application to detectors for fusion neutrons and include fission cross sections and activation cross sections around 14 MeV. The possible detectors range from conventional activation foils to fission fragment track detectors to in-line detectors based on reactions such as the $^9\text{Be}(n,\alpha)^6\text{He}$ reaction.

COMPILATION ACTIVITIES

The compilation and distribution of the microscopic data produced by this BES program is handled by the National Nuclear Data Center at the Brookhaven National Laboratory. The reader is referred to the Center for detailed data from this program as well as from the many other measurement programs.

MEASUREMENT AREAS NOT EMPHASIZED BY THE BES PROGRAM

It is important to recognize that this BES program cannot meet all the nuclear data needs for fusion and that many laboratories outside the program are contributing significantly to providing the required nuclear data. For example the cross section for a basic tritium breeding reaction, $^7\text{Li}(n,n't)^4\text{He}$, which is crucial to the success of nearly all fusion reactor designs, has been measured by several laboratories all of which are outside the BES program.

Particular areas not treated by the BES program and where nuclear data have been requested by the fusion community include photo-nuclear reactions, such as $\text{Ti}(\gamma,p)$, and activation and dosimetry cross sections other than standards. Integral experiments (benchmarks), integrated microscopic data

(such as direct measurement of kerma factors), sensitivity studies, and the evaluation of the microscopic data are not included in the program. The evaluation of the microscopic data is however of crucial importance in that the fusion user rarely uses anything other than evaluated or further processed data.

In addition certain data have been found difficult to measure. The neutron emission spectra for incident neutron energies between 8 and 13 MeV fall in this category.

CONCLUSION

This BES measurement program has made significant progress in satisfying the nuclear data needs for the development of fusion energy. (See Fig. 12 for a listing of measurements on iron for example). During the course of the program the data needs have evolved and changed somewhat so that further work is required. With the many new tools, both experimental and calculational, that have been developed through the program, these new needs should be met with greater accuracy, precision, and efficiency than ever before.

ACKNOWLEDGMENTS

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REFERENCES

1. E. T. Cheng, D. R. Mathews, and K. R. Schultz, "Magnetic Fusion Energy Program Nuclear Data Needs," General Atomics report GA-A17324 (October, 1983).
2. R. C. Haight, D. C. Larson, et al., "Office of Basic Energy Sciences Program to Meet High Priority Nuclear Data Needs of the Office of Fusion Energy," Lawrence Livermore National Laboratory report UCID-19930.
3. N. Jarmie, R. A. Hardekopf, R. E. Brown, F. D. Correll and G. G. Ohlsen, Nuclear Cross Sections for Technology, ed. J. L. Fowler, C. H. Johnson and C. D. Bowman, NBS SP-594, (Washington D.C., 1980), p. 733.

**Table I. Basic Energy Sciences Program to Meet the High Priority
Nuclear Data Needs of the Office of Fusion Energy.**

Institution	Activity
Brookhaven National Laboratory	Nuclear data compilation
Colorado School of Mines	Low energy fusion cross sections
Lawrence Livermore National Laboratory	(n, charged particle) reactions
Los Alamos National Laboratory	Low energy fusion cross sections; Data evaluation
Oak Ridge National Laboratory	(n,x γ), (n,xn), (n, charged particle) reactions; Model development
Ohio University	Neutron elastic and inelastic scattering; (n, charged particle) reactions
Rockwell International	(n, ^4He) reactions
Triangle Universities Nuclear Laboratory	Neutron elastic and inelastic scattering
University of Michigan	Standard cross sections
University of New Mexico	Standard cross sections

Table II -- from D. W. Kneff et al., J. Nucl. Materials 103, 1451 (1981).

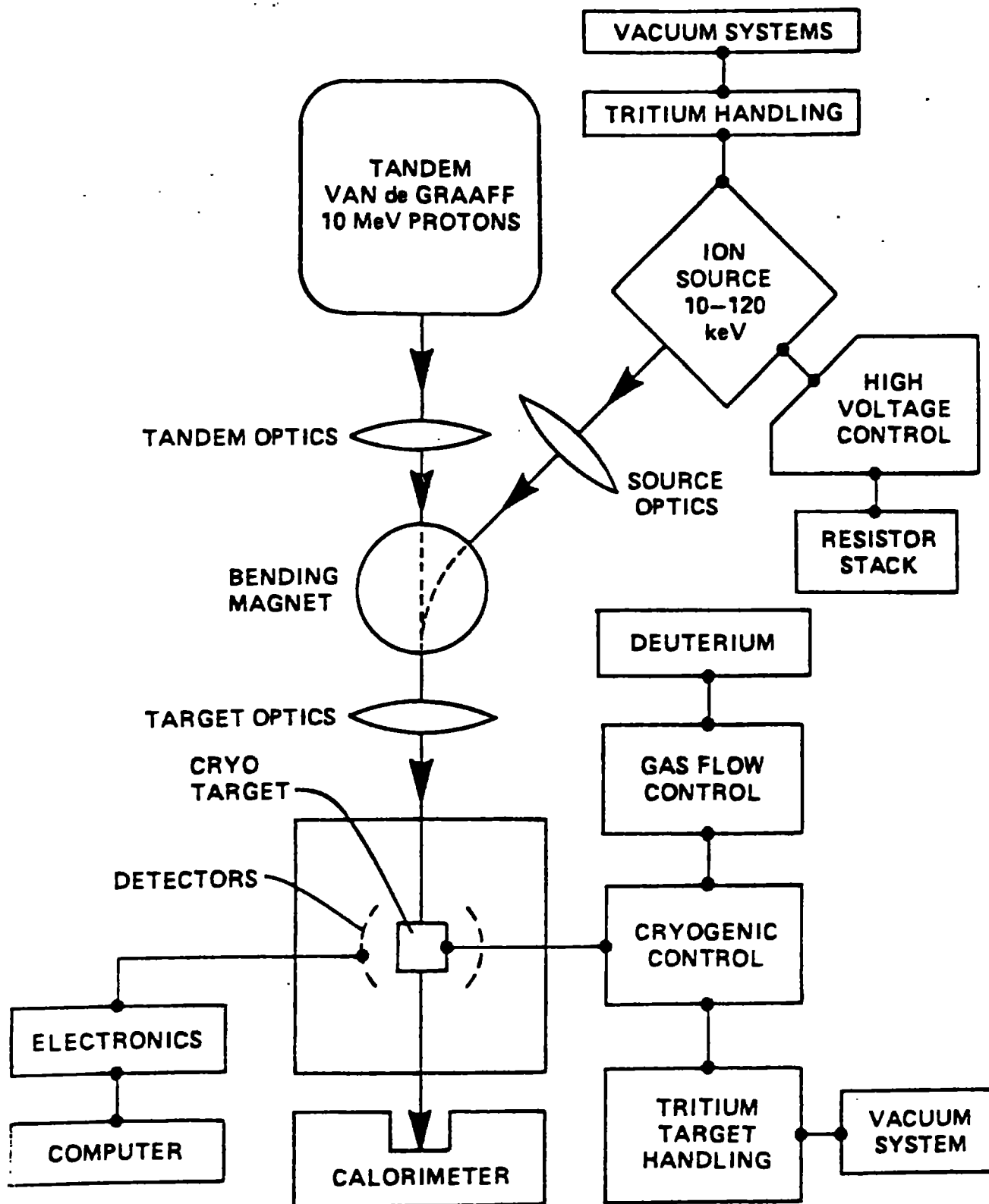
Helium generation cross sections for ~14.8-MeV Neutrons

Material	Measured Cross Section (mb)			Adopted Value (mb)	Charged-Particle Measurements ^{a)} (mb)
	RTNS-I Run 1	RTNS-I Run 2	RTNS-II		
C (diamond)	900 ± 70 ^{b)}			900 ± 70 ^{b)}	
Al	143 ± 7	145 ± 10		144 ± 7	121 ± 25
Ti	38 ± 3	37 ± 3		37 ± 3	34 ± 7
V	18 ± 2	18.7 ± 1.4		18.7 ± 1.4	17 ± 3
Cr	-	34 ± 4		34 ± 4	38 ± 6
Fe	48 ± 3	48 ± 3	49 ± 3	48 ± 3	43 ± 7
⁵⁴ Fe	-	88 ± 6	94 ± 7	91 ± 7	79 ± 13
⁵⁶ Fe	-	45 ± 4	47 ± 3	46 ± 3	41 ± 7
⁵⁷ Fe	-	-	33 ± 2	33 ± 2	
⁵⁸ Fe	-	20 ± 2	20 ± 2	20 ± 2	
Ni	98 ± 6	100 ± 7	101 ± 7	100 ± 7	97 ± 16
⁵⁸ Ni	-	116 ± 7	126 ± 9	121 ± 8	106 ± 17
⁶⁰ Ni	-	79 ± 6	80 ± 6	80 ± 6	76 ± 12
⁶¹ Ni	-	53 ± 4	49 ± 4	51 ± 4	
⁶² Ni	-	18 ± 6	22 ± 2	22 ± 2	
⁶⁴ Ni	-	61 ± 4 ^{c)}	9 ± 1	9 ± 1	
Cu	51 ± 3	51 ± 3	51 ± 4	51 ± 3	42 ± 7
⁶³ Cu	-	67 ± 5	64 ± 5	65 ± 5	56 ± 10
⁶⁵ Cu	-	17 ± 2	17 ± 1	17 ± 1	13 ± 3
Zr	10 ± 2 ^{b)}	10.2 ± 0.8	10.1 ± 0.7	10.1 ± 0.7	15 ± 3
Nb	17 ± 5			17 ± 5	14 ± 3
Mo	15 ± 2	15 ± 2	14 ± 1	14 ± 1	20 ± 6
⁹² Mo	-	31 ± 2	31 ± 2	31 ± 2	36 ± 7
⁹⁴ Mo	-	22 ± 2	22 ± 2	22 ± 2	28 ± 6
⁹⁵ Mo	-	17 ± 2	17 ± 1	17 ± 1	24 ± 5
⁹⁶ Mo	-	11 ± 1	12 ± 1	12 ± 1	18 ± 4
⁹⁷ Mo	-	10 ± 1	10 ± 1	10 ± 1	
⁹⁸ Mo	-	23 ± 2 ^{c)}	22 ± 2 ^{c)}	c)	
¹⁰⁰ Mo	-	3.8 ± 0.5	3.8 ± 0.3	3.8 ± 0.3	
Au	-	0.72 ± 0.09	0.50 ± 0.04	0.50 ± 0.04	
316 SS	57 ± 4			57 ± 4	48 ± 7

^{a)}R. C. Haight, et al., References 9-12^{b)}Unetched samples. Corrections for α-recoil effects have not been made; this is reflected in increased cross section uncertainties^{c)}See text

Figure Captions

1. Block diagram of the Low Energy Fusion Cross Section facility at the Los Alamos National Laboratory.
2. Measured cross section for the $D(t,n)^4\text{He}$ cross section at low energies (data from Los Alamos).
3. Legendre polynomial coefficients for neutron scattering from ^{11}B (data from Ohio University).
4. Analyzing powers for the scattering of neutrons from ^{58}Ni (data from Triangle Universities Nuclear Laboratory).
5. Neutron emission from copper as a function of incident neutron energy (data from Oak Ridge National Laboratory).
6. Gamma rays from neutron bombardment of iron as a function of incident neutron energy (data from Oak Ridge).
7. High resolution gamma rays from neutron bombardment of ^{56}Fe (data from Oak Ridge).
8. Use of a magnetic quadrupole lens transport system reduces the background in (n,charged particle) experiments (Ohio University and Lawrence Livermore National Laboratory).
9. An evacuated time-of-flight pipe for charged particles allows particle identification in (n,charged particle) experiments (Ohio University).
10. Experimental data for (n,p) proton emission cross sections compared with nuclear reaction (Hauser-Feshbach) calculations (Livermore).
11. Block diagram of apparatus to measure helium produced by neutron bombardment (Rockwell International).
12. BES measurements of neutron interactions with iron, data needed for the development of magnetic fusion energy.



LOW ENERGY CROSS SECTION EXPERIMENT

Figure 1

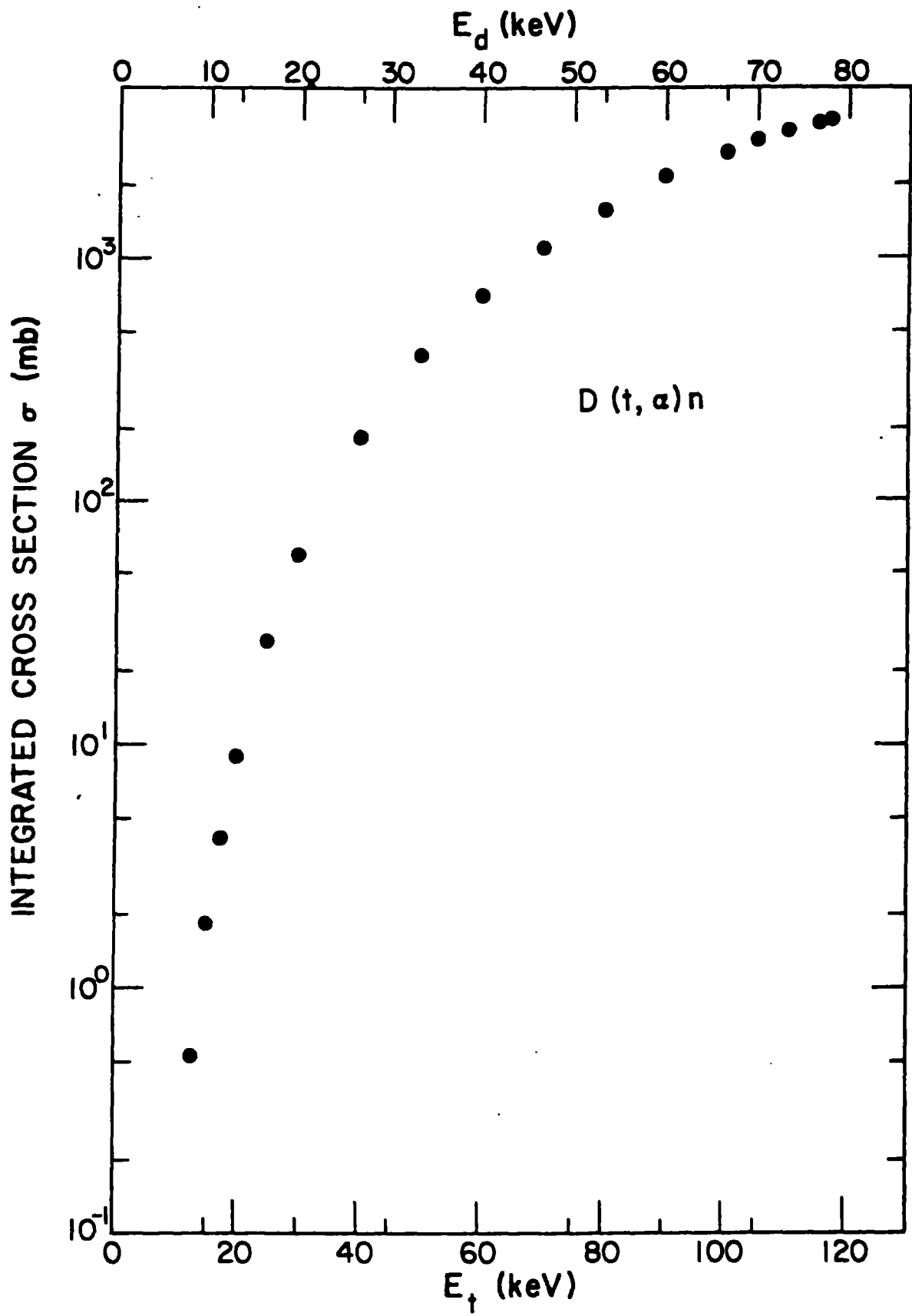
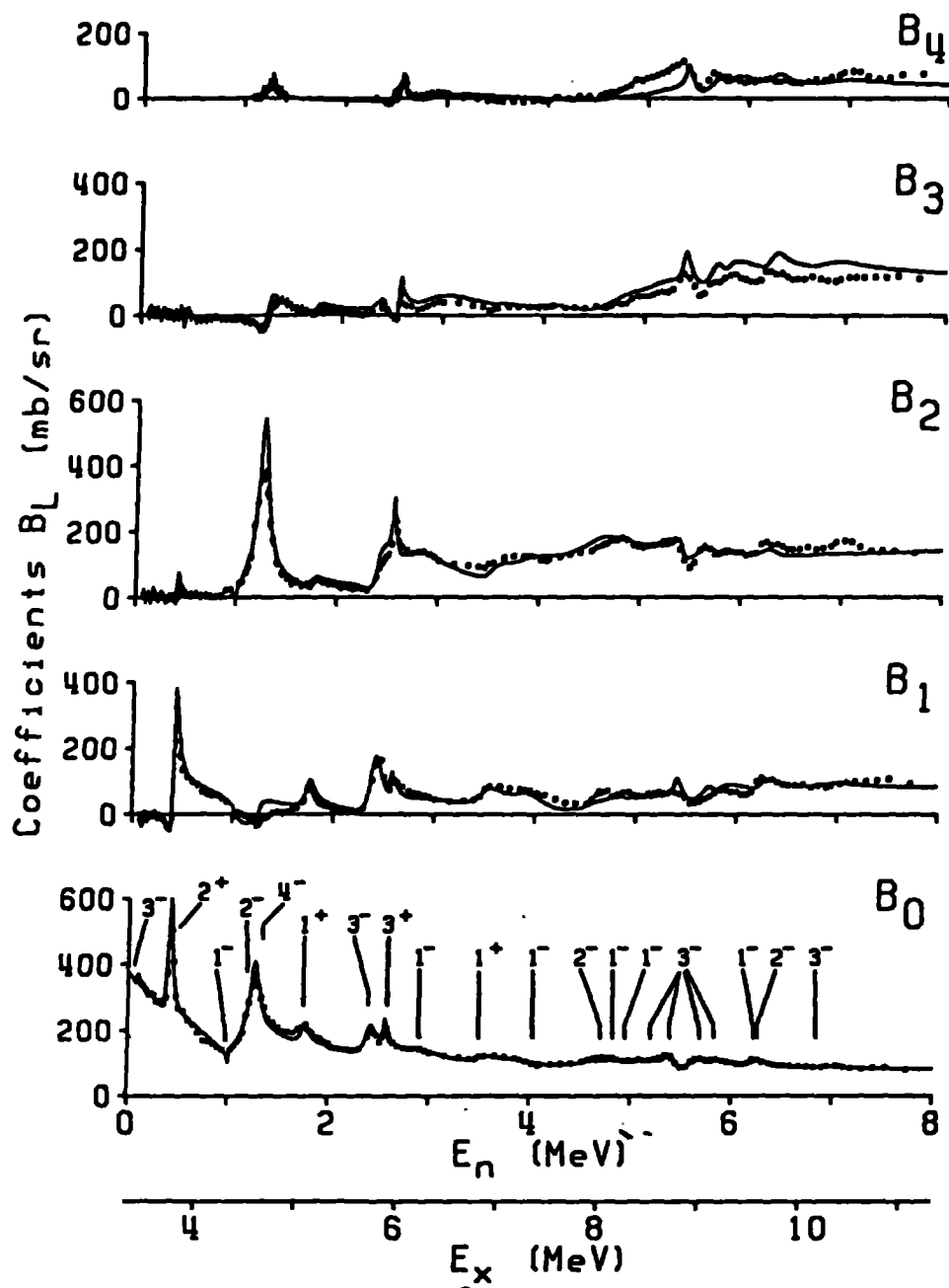


Figure 2

$^{11}\text{B} (n, n) ^{11}\text{B}$



5. Coefficients B_L in the Legendre polynomial expansion of the differential $^{11}\text{B}(n, n)^{11}\text{B}$ cross section for $L = 0$ to 4 . The curves are the present R -matrix fits to the data.

Figure 3

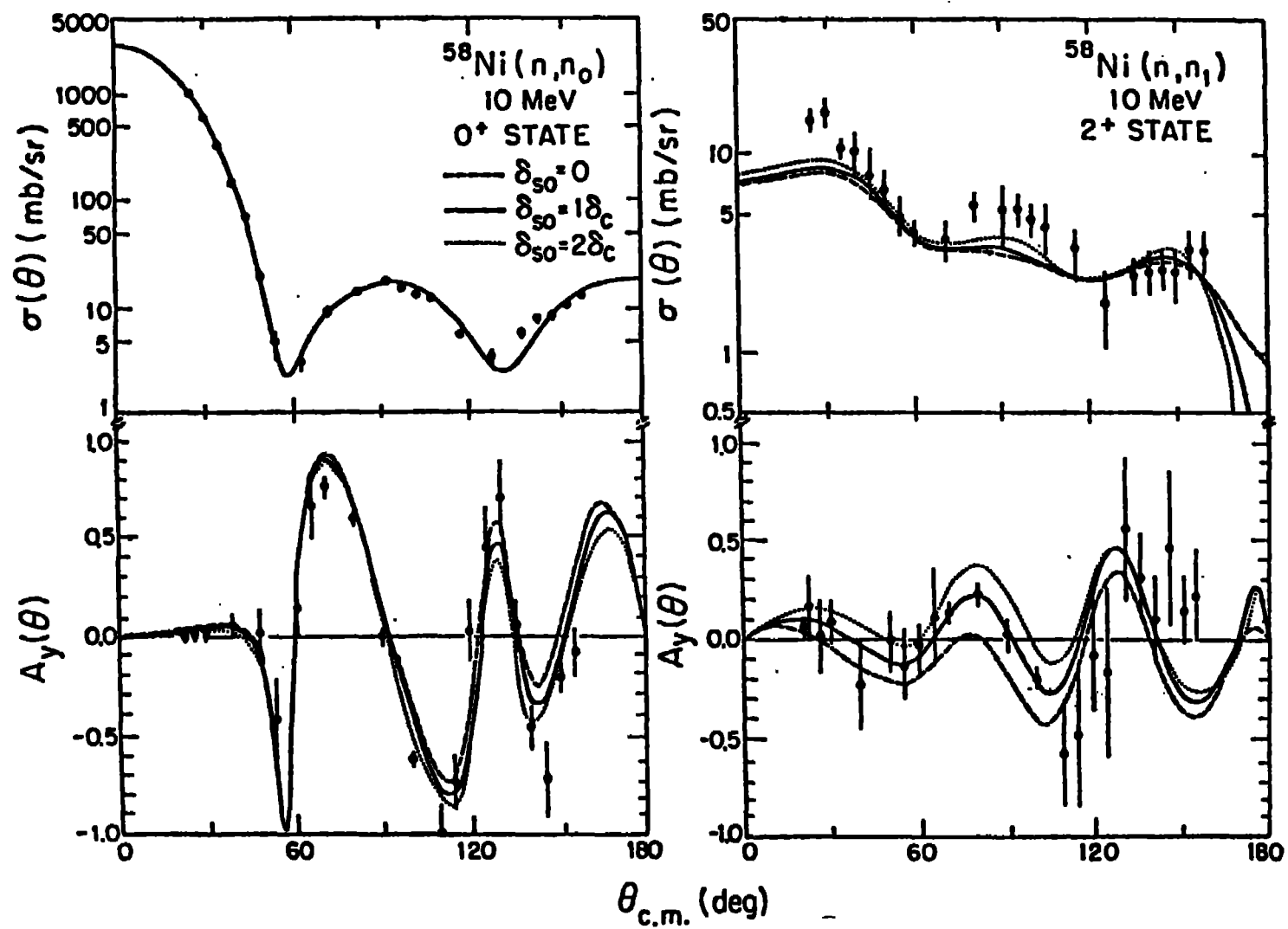


Figure 4

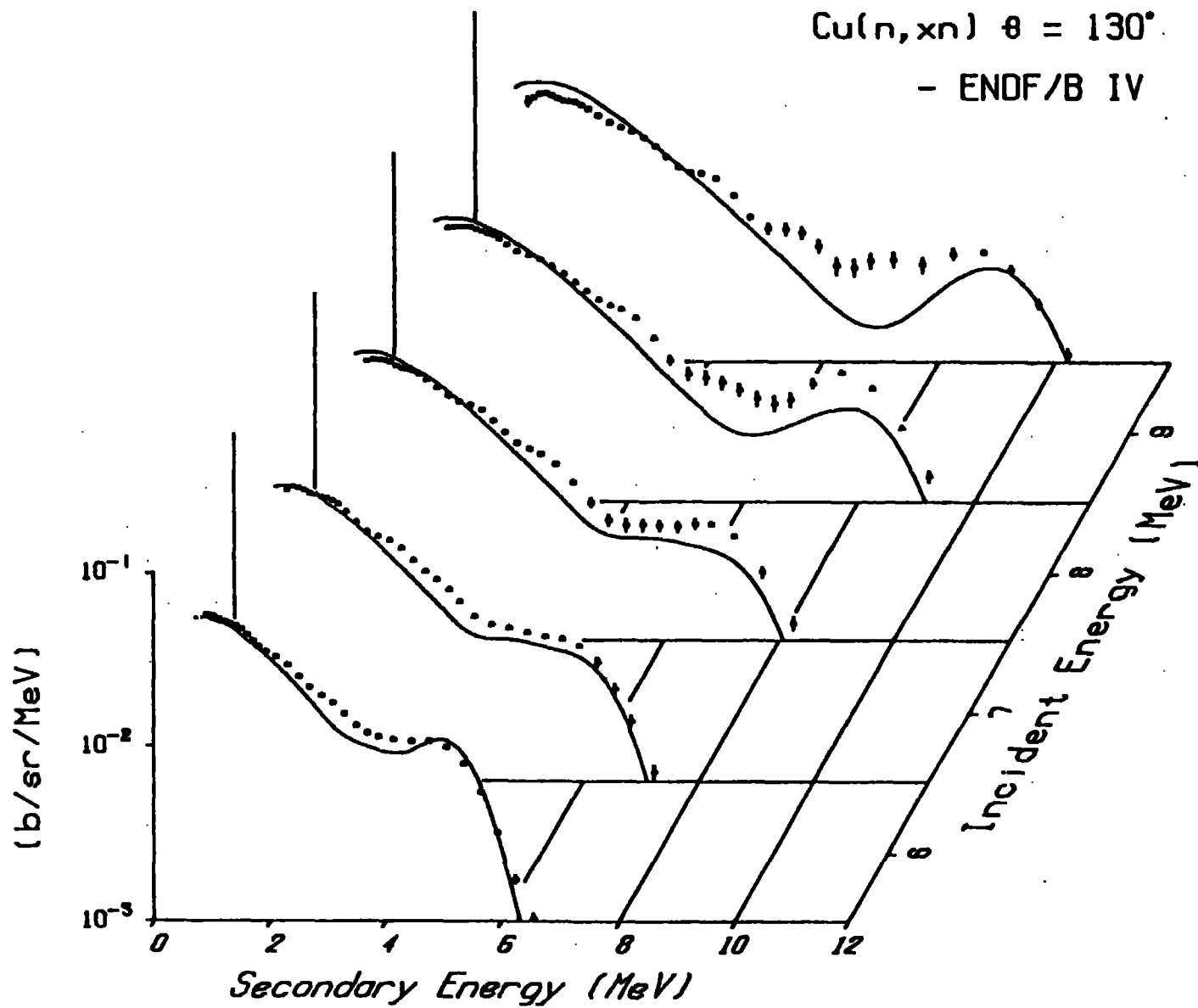


Fig. 13. Secondary neutron spectra versus scattered and incident neutron energy.

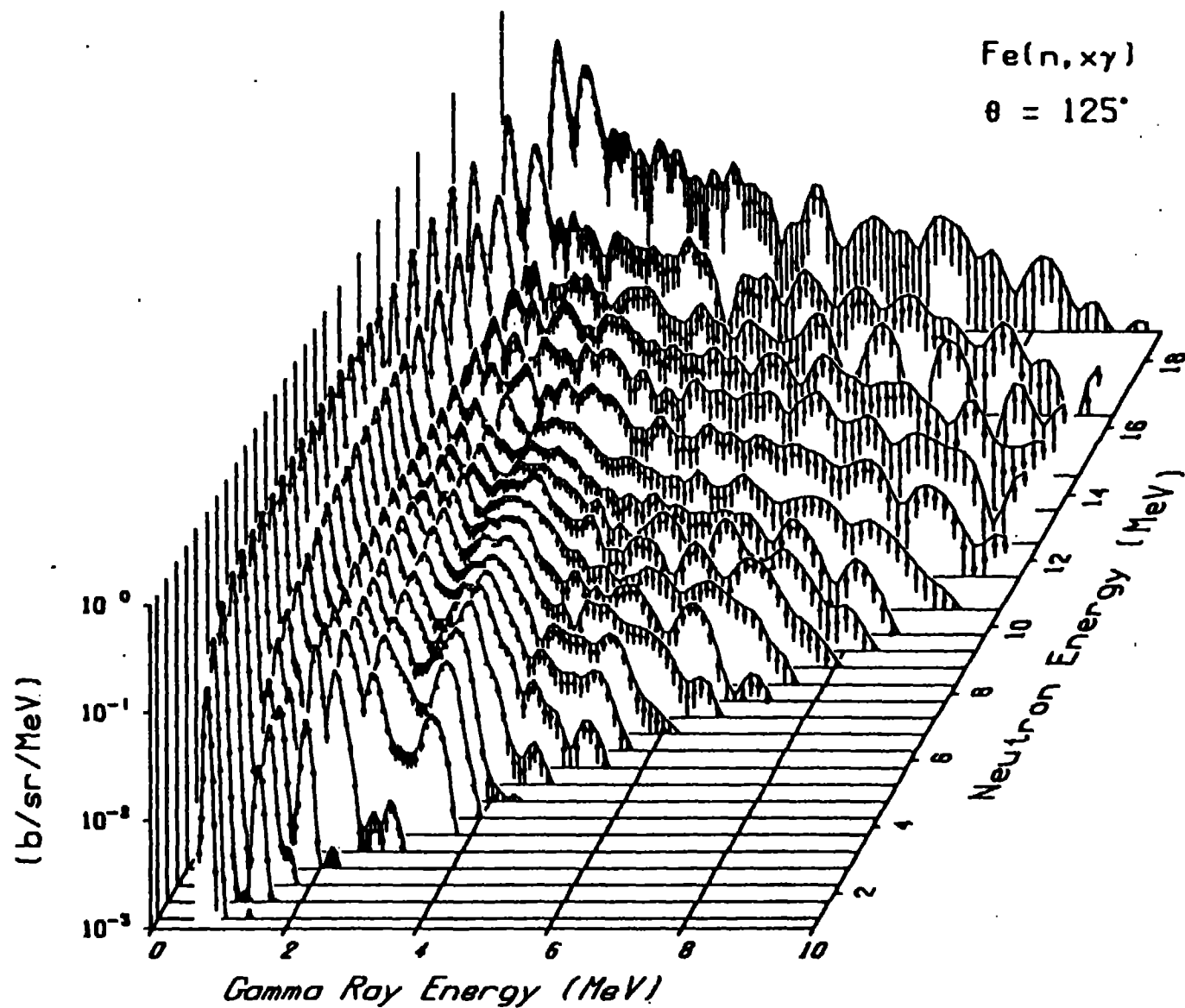


Fig. 2. Three-dimensional representation of the cross section variation as a function of neutron and gamma-ray energy.

$^{56}\text{Fe}(n, X\gamma)$

$^{56}\text{Fe}(n, n'\gamma) \text{ } ^{56}\text{Fe} - a$
 $^{56}\text{Fe}(n, 2n\gamma) \text{ } ^{55}\text{Fe} - b$
 $^{56}\text{Fe}(n, n\alpha\gamma) \text{ } ^{52}\text{Cr} - c$
 $^{56}\text{Fe}(n, 3n\gamma) \text{ } ^{54}\text{Fe} - d$
 $^{56}\text{Fe}(n, np\gamma) \text{ } ^{55}\text{Mn} - e$

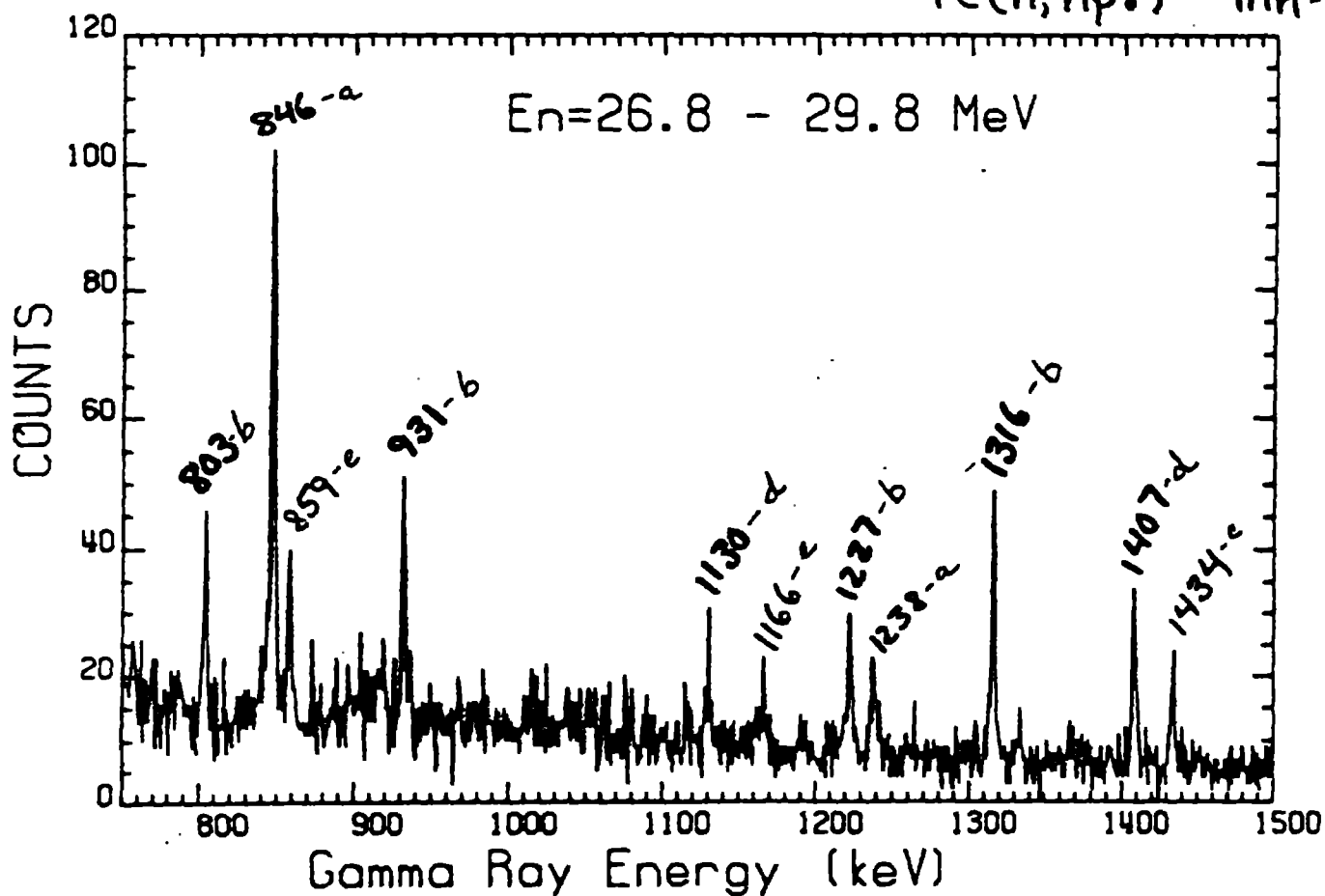


Figure 7

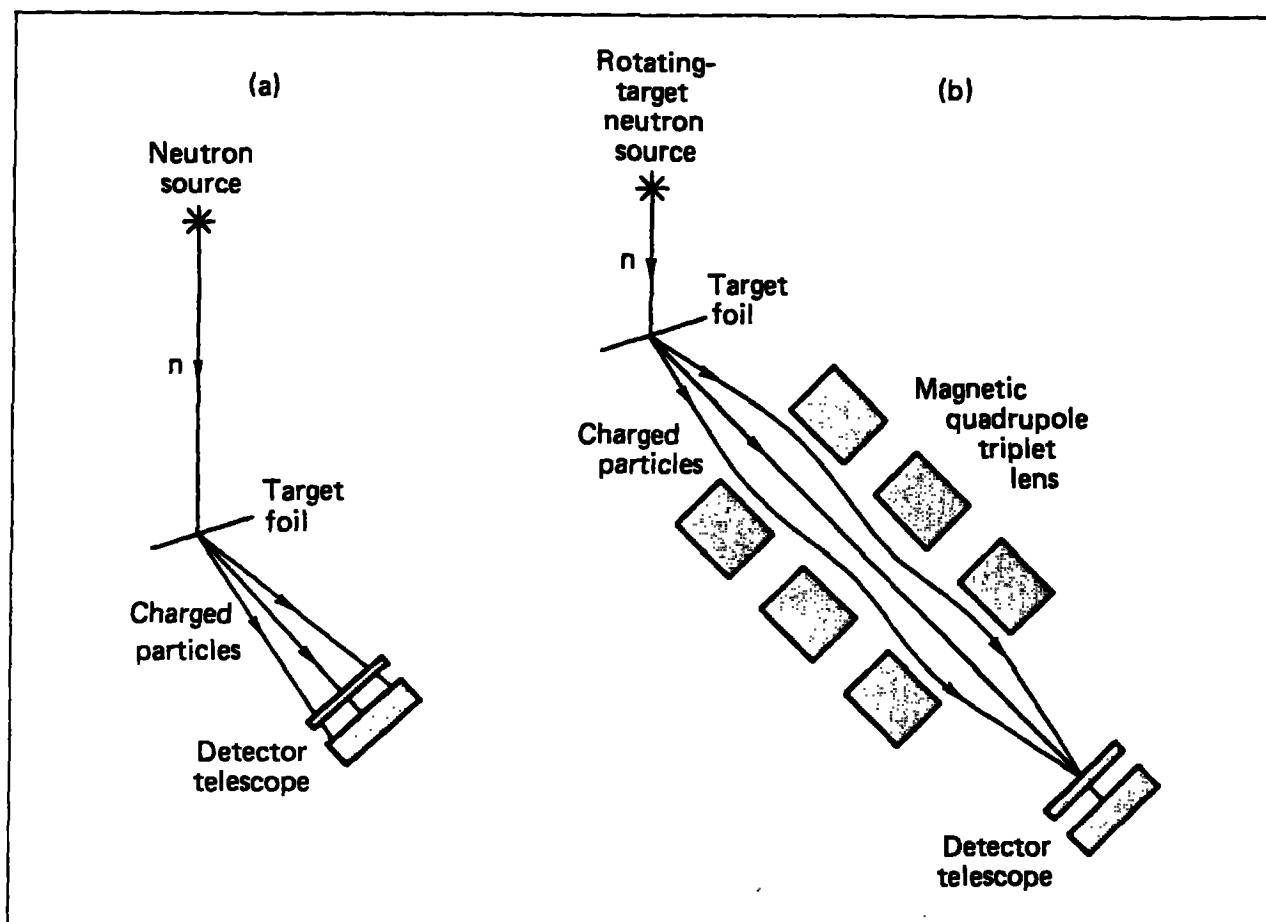


Figure 8

SCINTILLATOR LIGHT OUTPUT

TIME OF FLIGHT

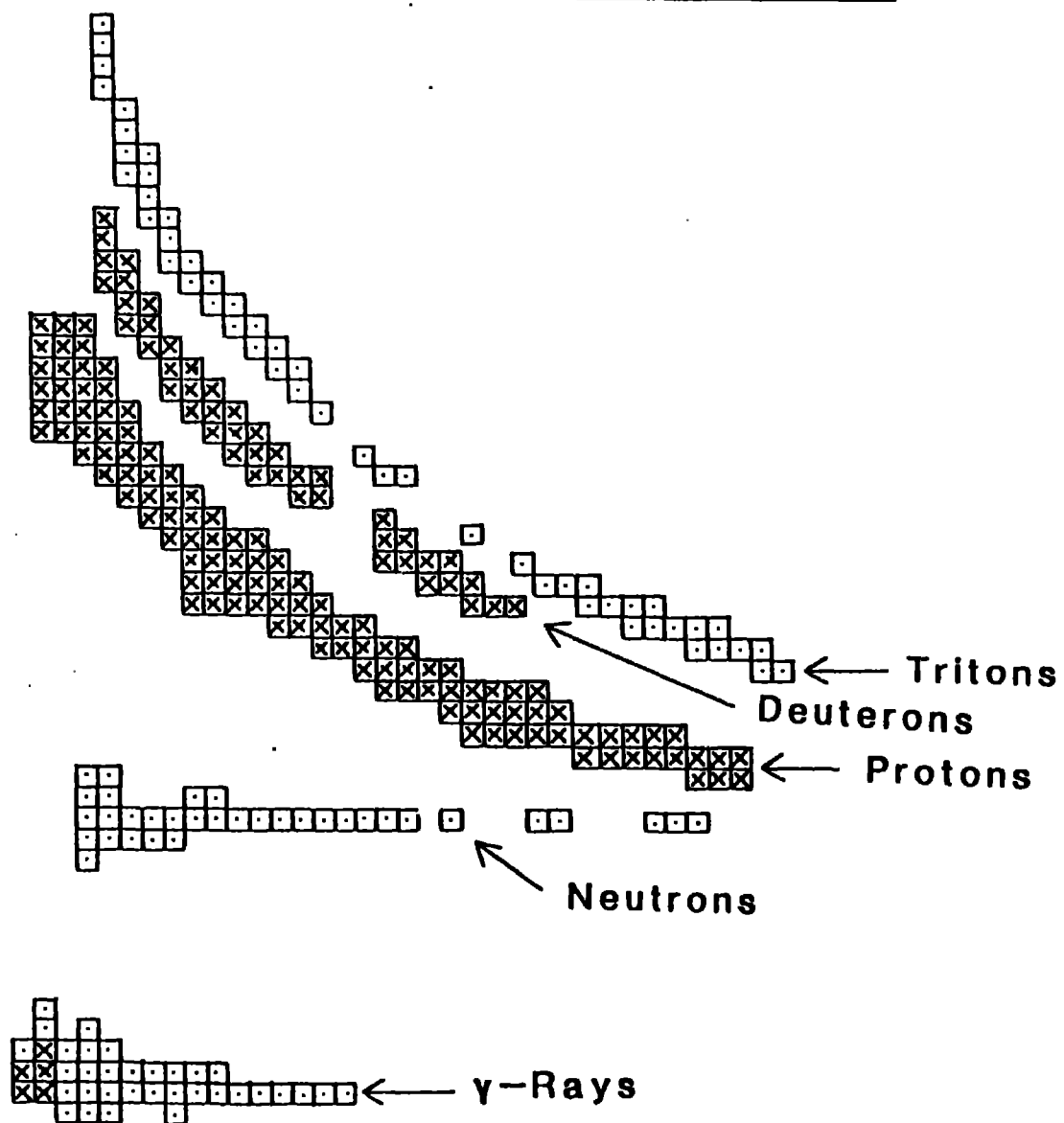


Figure 9

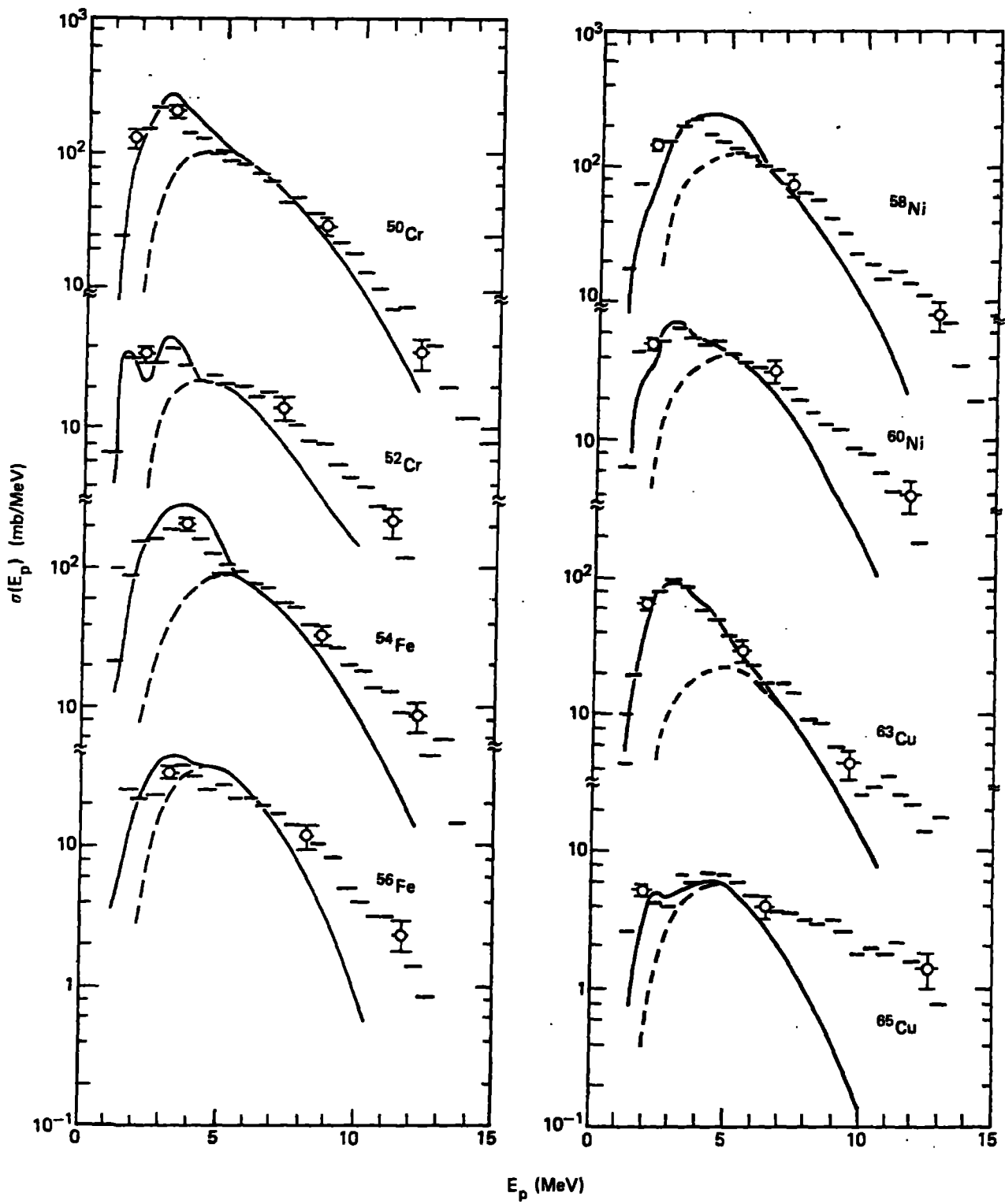
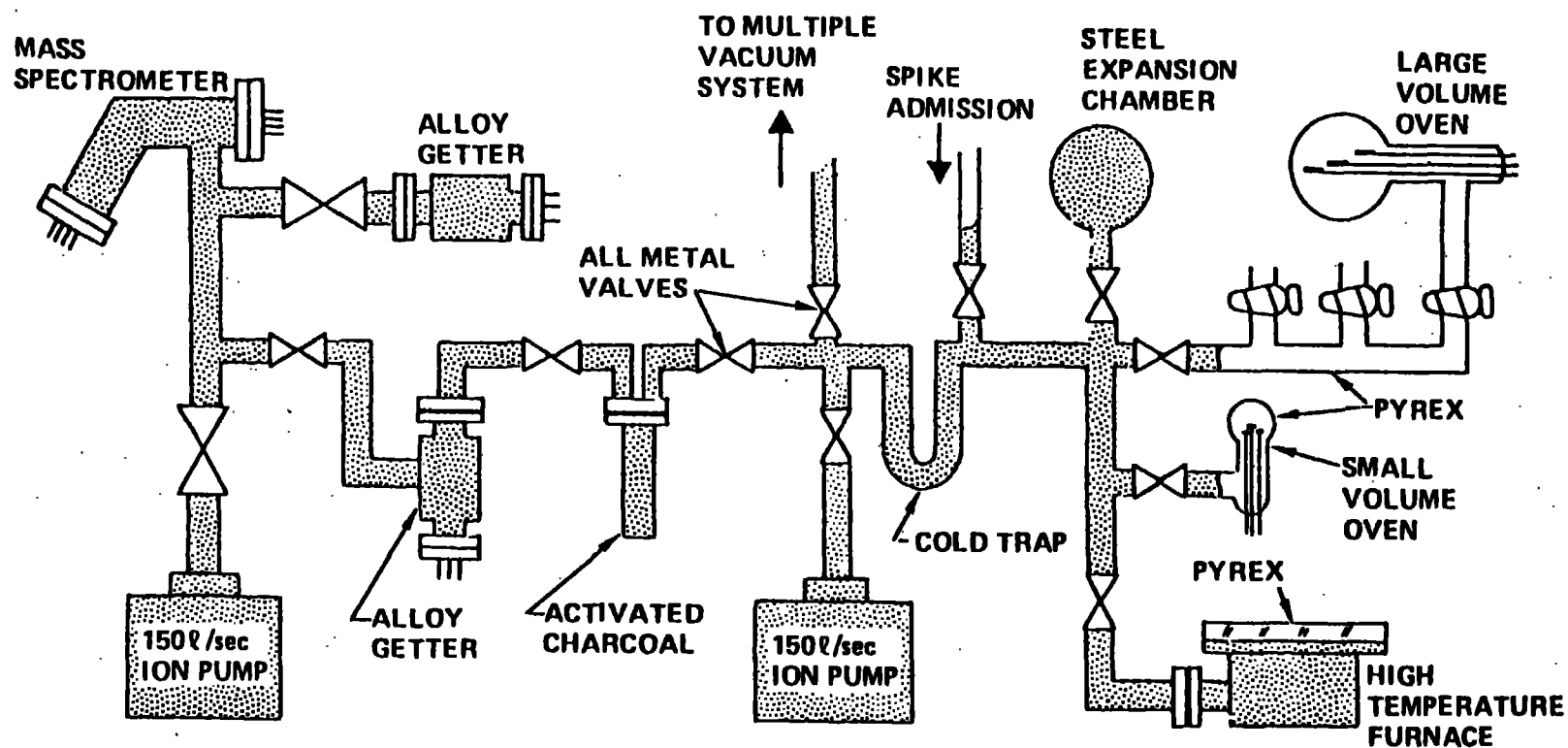


Figure 10

MASS SPECTROMETER SYSTEM



Fe	54	(n,Xz)	15 MeV	1	Laboratory index
	54	(n,X α)	15	5	
	54	(n,n)	8,10,12,14	6	
	54	(n,n')	8,10,12,14	6	
	56	(n,n)	26	4	
	56	(n,X γ)	.16-40	3	
	56	(n,n')	26	4	
	56	(n,Xz)	15	1	
	56	(n,X α)	15	5	
	56	(n,n)	8,10,12,14	6	
	56	(n,n')	8,10,12,14	6	
	57	(n,X γ)	.16-21	3	
	57	(n,X α)	15	5	
	58	(n,X α)	15	5	
	N	total	2-80	3	
	N	(n,Xz)	15	1	
	N	(n,X α)	15	5	

Figure 12